A Revolutionary Method in Optical System Design

Inventor: Jiang; Jianfeng (San Jose, CA)

Assignee:

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Reference Cited

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FIELD OF INVENTION

This invention relates to optical system design, more specifically to lens design, image chip design and lens module design.

BACKGROUND OF THE INVENTION

Optical systems are increasingly penetrating into our everyday life. Digital Cameras, Projectors, Camcorders, and new generations of cellular phones with cameras, just to name a few common products.

A typical optical system consists of a set of lens and an image chip.
The image chip is typically made of either CCD (charge-coupled-device) or CMOS (complementary-Metal-Oxide-Semiconductor). It senses the image formed by the lens set and converts it into electrical signals (either analog or digital).
The lens is made of plastics or glass with spherical or aspherical surface, it bends the light from the object and forms an image at the image plane. Plastic lens is very cheap but of less quality. Glass lens is used for optical systems with higher resolution and less temperature-related distortions. Glass lens is more expensive than plastic lens. Lens with spherical surface is much easier to manufacture and much cheaper than lens with aspheical surface.

There is no lens set that can form an exact image of the object, aberrations are always present in the images. For example, if the object is a point light source, its image will not be a point, rather the image will be a haze surrounding a bright point. The image of a point object is called **Point-Spread-Function (PSF)**. The aberrations of lens are usually classified as: Spherical Aberration, Coma, Astigmatism, Distortion and Chromatic Aberrations. The Point-Spread-Function (PSF) contains all of these informations.

As shown in **Fig. 1**, If the optical system is rotationally symmetrical about the optical axis which is practically the case, then a ray of light from the point **($y = h$, $x = 0$)** in the object that passes through the lens at a point defined by its polar coordinates **(s, θ)** will intersect the image surface at **(x', y')** in the general forms as follows:

$$Y' = A_1 S \cos\theta + A_2 h + B_1 S^3 \cos\theta + B_2 S^2 h (2+\cos 2\theta) + (3B_3 + B_4) sh^2 \cos\theta + B_5 h^3 + C_1 S^5 \cos\theta + (C_2+C_3\cos 2\theta) s^4 h + (C_4 + C_6\cos^2\theta) s^3 h^2 \cos\theta + (C_7+C_8\cos 2\theta) s^2 h^3 + C_{10} sh^4 \cos\theta + C_{12} h^5 + D_1 S^7 \cos\theta + \ldots \quad (1)$$

$$X' = A_1 s \sin\theta + B_1 S^3 \sin\theta + B_2 s^2 h \sin 2\theta + (B_3 + B_4) sh^2 \sin\theta + C_1 s^5 \sin\theta + C_3 s^4 h \sin 2\theta + (C_5 + C_6\cos^2\theta) s^3 h^2 \sin\theta + C_9 s^2 h^3 \sin 2\theta + C_{11} sh^4 \sin\theta + D_1 s^7 \sin\theta + \ldots \quad (2)$$

The objective of lens design is to choose from different glass material, choose the number of lens, the shape and size of each lens, so that the whole lens set meets the specifications including focal length, view angle, resolution, distortion, etc.

Traditionally, the lens design and image chip design are two independent processes done by independent companies. The lens designers optimize the lens design to achieve as less aberrations and distortions as possible, which usually results in many lens in high resolution systems (typically 3 to 12 lens). To reduce the number of lens, some manufacturers use aspherical lens (non-spherical surface) which is very expensive. On the other hand, the rapid advance in VLSI technology makes the digital-signal-processing capability of image chips very high with little cost. It is foreseeable that as technology advances, the resolution requirements of the lens system are increasingly higher which will put lots more burdens on the lens design. The essence of the invention is to make full use of the powerful digital-signal-processing-capability of the image chip to correct some aberrations of the lens set, thus reduce the aberration requirements for the lens design. By doing this, the number of required lens is reduced and the overall cost of the optical systems (lens + image chip) is reduced. That is, smaller and cheaper optical system can be achieved using this invention.

SUMMARY OF THE INVENTION

The invention is about the optimization of the optical system design (including both lens and image chip). Using the proposed design method for both lens and image chips, higher resolution with less cost and smaller size are possible.

Firstly, for existing lens, the Point-Spread-Functions of selected object points are measured (Refer to **Fig.3, 4, 5 & 6** for the setup) with a high resolution image sensor. Note that in order to extract as much information as possible about the lens, the PSF corresponding to three colors (typically Red, Blue or Green) are measured separately, since most of the image chips have intermingled color filters. Once all the PSF are measured, the parameters describing the lens aberrations can be extracted. Using a mathematical technique called deconvolution or other techniques, the aberrations caused by the lens can be corrected using the proposed image chips(will be described later). Thus, the existing lens design can be re-used for higher resolution optical systems with a higher-resolution image chip with proposed correction capability. In this way, considerable costs of lens re-design are saved for higher resolution optical systems.

Secondly, for optical systems of which the lens must be re-designed, much less cost and smaller size optical systems can be achieved by relaxing the aberration requirements on the lens system, that is, less number of lens can be used to achieve the desired high resolution using the proposed error correction techniques. This is extremely useful for cell-phones cameras, in which the camera must be made as small as possible.

Theoretically, the proposed aberration correction technique can be proven as follows.

As shown in **Fig. 2** (without loss of generality, a two-dimentional case is illustrated.) If the object is a vertical line with **M** point light sources with equal intensity, and there are **N** pixels on the image chip. For each point light source, its image is a Point-Spread-

Function which will look like a haze surrounding a bright spot. So long as the lens aberrations are not too big, the size of the Point-Spread-Function should be really small.

For each object point **i**, its intensity at image point **j** can be denoted as S_{ij}, where S_{ij} is a representation of the Point-Spread-Function.

For an arbitrary object, if the illuminance of the *i*-th object point is denoted by $\mathbf{O}_i$, its image at *j*-th pixel is denoted by $\mathbf{I}_j$, then using matrix format, the lens system can be described as:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ \cdot \\ \cdot \\ I_n \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & \cdot & \cdot & S_{1m} \\ S_{21} & S_{22} & S_{23} & \cdot & \cdot & S_{2m} \\ S_{31} & S_{32} & S_{33} & \cdot & \cdot & S_{3m} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ S_{n1} & S_{n2} & S_{n3} & \cdot & \cdot & S_{nm} \end{bmatrix} * \begin{bmatrix} O_1 \\ O_2 \\ O_3 \\ \cdot \\ \cdot \\ O_m \end{bmatrix}$$

Or to write it concisely in vector form:

$$\mathbf{I} = \mathbf{S} * \mathbf{O} \qquad (3)$$

Where **I** is a vector with **n** elements denoting the intensity at each image point,
O is a vector with **m** elements denoting the intensity at each object point,
And **S** is the matrix characterizing the transformation from object points to image points, which contains the Point-Spread-Function of all the points.
Ideally, for a perfect lens system, the S matrix is a unit matrix, that is, every object points corresponds to one image point. In reality the images are somewhat blurred.
If the lens aberrations are not too big, then the S matrix will be a sparse matrix, that is, there are only a few non-zero elements. For example, the first column stands for the

Point-Spread-Function of the first object point. If the point-spread-function covers only 5 images points, then only the first 5 elements are non-zero.

Theoretically once S matrix is extracted from measurements, then for any light source, its true image can be derived from

$O = S^{-1} * I$. Where **S^{-1}** is the inverse matrix of the S matrix. **(4)**

It should be noted that for different wave length lights, the S matrix will be slightly different because of the lens aberrations.

This is the essence of the invention, use some pre-designed object (one example is shown in **Fig 3&4**, Of which there are many nearly-point-like light sources), measure the Point-Spread-Functions using very high resolution image chips, do the measurement for Red, Green and Blue lights, the S matrix is thus extracted. And the inverse matrix **S^{-1}** can also be calculated and the result will be stored in the proposed image chip, the proposed image chip will do a simple conversion according to **formulae (3) & (4)** to achieve a good image with the lens aberrations corrected.

Another example of measuring the Point-Spread-Function of the lens is shown **in Fig. 5 &6,** where we can approximate the PSF by a circular distribution with radius ε, by measuring the images of evenly separated circular sources as shown in **Fig. 5**, the radius ε can be calculated as:

$$\varepsilon = Ri - (Li/Lo)*Ro$$

It should also be pointed out that by using both the measured S-matrix and the theoretical lens aberrations formulae (1) & (2), some faster image correction algorithms are possible.

DESCRIPTION OF THE DRAWINGS

Fig.1 shows a ray of light from the point **(y =h, x=0)** in the object that passes through the lens at a point defined by its polar coordinates **(s,θ)** will intersect the image surface at **(x', y')**, where x' & y' can be generally described by formulae (1) & (2)

Fig. 2 shows an optical system consists of M point light sources with equal illuminance, and an image chip with N pixels.

Fig. 3 shows a proposed set-up for measuring the Point-Spread-Functions of the lens system. Shine collimated light on an opaque plate with small holes as point-like light sources, measure the image with high resolution image chip. The S matrix can then be constructed.

Fig. 4 shows one example of the opaque plate with small holes, the hole separations are smaller as they are further away from the center.

Fig. 5 shows another example of measuring the Point-Spread-Functions using opaque plate with small holes (or transparent plate with circular dark patterns.)

Fig. 6 shows the mathematical approximations of Point-Spread-Function.